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THE SUPERCONDUCTING CHICAGO CYCLOTRON MAGNET - AN OLD MAGNET WITH A NEW PAIR OF ENERGY EFFICIENT COILS*

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Abstract

Significant electrical power can be saved by replacing existing water-cooled copper coils with superconducting ones. This paper describes a DOE-Fermilab energy conservation project in which a pair of superconducting tori 5.25 m in diameter have been constructed to replace the copper coils, built in 1949, of the 170-inch Chicago Cyclotron, now in use at Fermilab as an analysis magnet. The superconducting magnet, with a stored energy of 32.5 MJ, was fabricated in-house at Fermilab. Engineering concepts, design and optimization of the coil, support structure and cryogenic system are described. In particular, the major support, a composite column capable of a collapse load of 1.33×10^6N and an expected heat leak of 120 mW will be described in detail. Practical problems encountered during the construction phase are discussed and test results presented.

Introduction

Fermi National Accelerator Laboratory has been active in the development and application of superconducting magnets since the founding of the laboratory. This frontier magnet technology is being applied to Doubler/Saver magnets, secondary beam transport magnets, experimental area analysis magnets and energy conservation coil conversion projects. The Chicago Cyclotron Magnet (CCM) Conversion Project belongs to the last category.

The Chicago Cyclotron magnet was constructed to provide the magnet field for a 450 MeV Cyclotron built at University of Chicago around 1949. After the Cyclotron was decommissioned, the magnet was transported to Fermilab in 1971 and reassembled for use as an analysis magnet in the FNAL Muon Laboratory where it resides currently. At full excitation, the existing copper coils consume 2.5 MW of electrical power. The savings brought about by having the coils superconducting can be formulated in terms of 1) more effective use of electrical power: that the 2.5 MW required to run the conventional CCM be used to power the Main Ring, hence producing higher intensity beams or cutting down the time duration for high energy physics experiments; or 2) monetary benefit: economic savings of up to $200,000 can be generated by running the magnet superconducting, continuously for a year.

Design Philosophy & Requirements

To conserve and save is our primary objective. The amount of financial benefit brought about by a superconducting magnet is primarily determined by the heat transfer into the liquid helium environment. The heat leak, must, therefore, be reduced to a minimum without sacrificing reliability or cost. The break even point (the point at which LHe plus operation cost = power cost) for the CCM project is a liquid helium boil-off rate of about 40 ℓ (liquid liters)/hour, or ~28 watts.

Magnet Field & Force Calculations

An important aspect of superconducting magnet design is magnetic field calculation. The more accurately the directions and magnitude of the forces involved are known, the easier it is to design an optimized (with respect to heat leak) mechanical support system. The magnetostatic calculation was done using the axisymmetric form of TRIM[1] and the results checked with GFUN-3D.[2] A three-dimensional program like GFUN-3D is required for this case because of the asymmetry of the magnet iron (Fig. 1). Detailed results have been published as a Fermilab internal report.[3] The magnet parameters are presented in Table I.

Table I

Magnet Parameters

Configuration:	Split solenoid (2 coils)
Winding inside diameter:	5.19 m (204.4 in.)
Radial thickness of winding:	14.2 cm (5.6 in.)
Vertical dimension of each coil:	11.7 cm (4.6 in.)
Spacing between coils:	1.85 m (73 in.)
Number of turns per coil:	1000
Operating current:	1000 A
Length of conductor per coil:	16.8 km
Current density in conductor:	9568 A/cm^2
Coil current density (average):	6017 A/cm^2
Central field:	1.5 T
Maximum field in coil:	2.85 T
Shelf inductance:	65 H
Stored energy:	32.5 MJ
Total vertical force towards iron for each coil ΣF_Z:	5.2×10^6N (1.17×10^6 lbf)
Vertical force per unit length on each coil, F_r/ℓ:	3.1×10^5N/m (1777 lbf/in.)
Radial force per unit length on each coil, F_z/ℓ:	2.7×10^5N/m (1545 lbf/in.)
Radial decentering force, dF_r/dr:	7.95×10^5N/m (4500 lbf/in. displacement)
Nitrogen storage:	1850 liquid liters
Nitrogen use rate (measured):	300 liters/day (12.5 ℓ/hr)
Helium storage:	2000 liquid liters
Helium use rate (measured):	< 310 liters per day (< 13 ℓ/hr)

Coil Design and Construction

The CCM conductor used is a soldered cable with a Cu:SC:solder (70/30) ratio equal to 9.75:1:2.42. It consists of six 0.69 mm NbTi strands and eight 0.69 mm Cu strands soldered around a solid rectangular Cu core. The high copper to superconductor ratio ensures a safe margin for intrinsic stability. The coil structure (Fig. 2) is well defined and readily analyzed. Each coil was wound using a "wet lay-up" technique, with the insulating spacers wetted with epoxy and the whole coil then thermally cured to form a solid composite structure. The spacers serve a triple purpose: a) as load bearing members that transmit the electromagnetic

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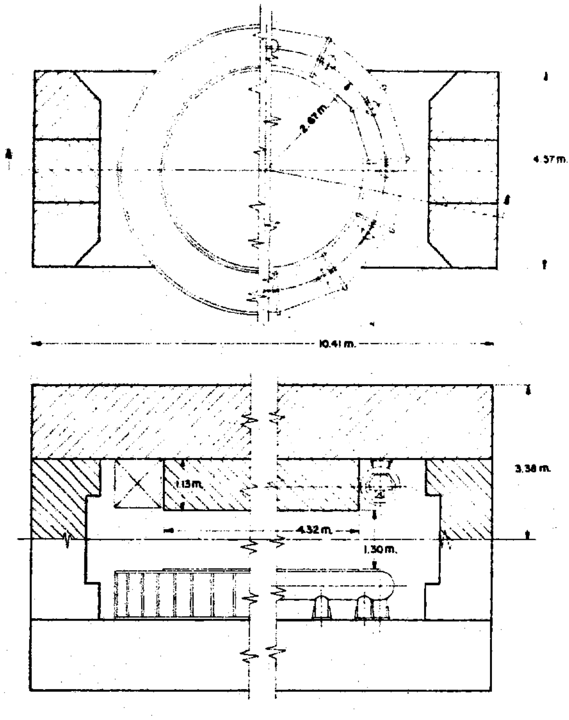


FIG. I : A SECTION OF BOTH THE OLD AND NEW CCM

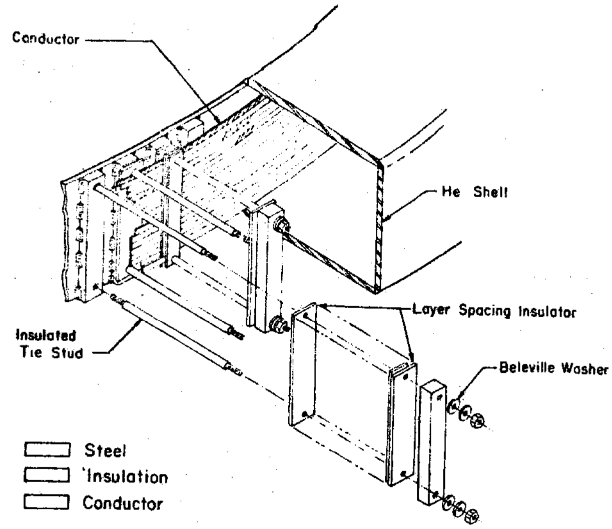


FIG. 2 COIL STRUCTURE

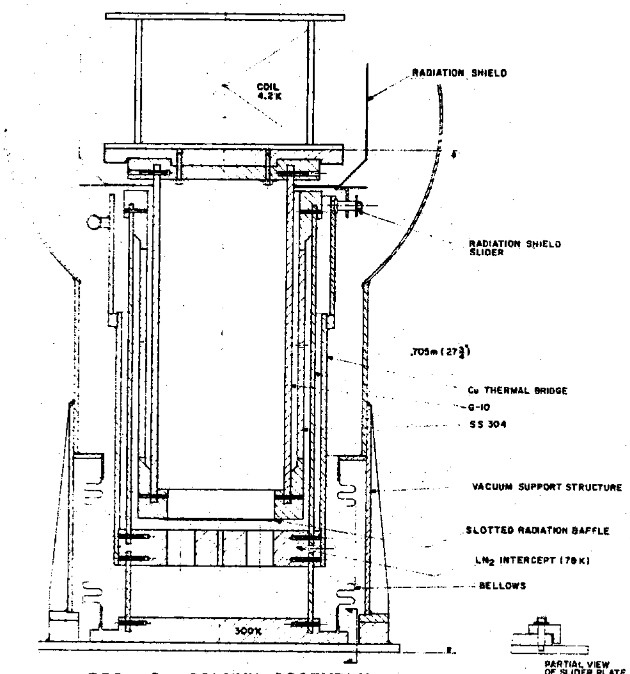


FIG. 3 COLUMN ASSEMBLY

forces through the entire coil, b) as electrical insulators and c) to provide cooling channels through the coil. Individual conductors can then be treated analytically as a continuous beam on multiple supports. The radial force on each coil is carried by the helium vessel (SS 304) while the vertical force is reacted with 12 specially designed composite support columns, equally spaced at 30° around the coil (Fig. 1). Each coil is attached to the vessel wall with insulated mounting studs as shown in Fig. 2.

The primary support structure (Fig. 3) consists of a four-tube (three G-10 and one SS 304) composite column with a LN_2 temperature heat intercept and a slider mechanism to take care of the differential contraction between the coil and the vacuum shell. The sliding material is made of bronze impregnated Teflon, with an extremely low coefficient of sliding friction (< 0.05). A thin-walled bellows completes the high vacuum circuitry while permitting motion of the columns. Extensive testing had been carried out with a prototype. The column has a collapse load of 1.33×10^6 N in compression, tensile strength of 5.18×10^4N and a design heat leak of less than 120 mW. The lateral stiffness constant was measured to be 3.43×10^{-4} mm/N (6.0×10^{-5} in/lbf). Under normal operating conditions (cryogenic temperature), each column sees a compressive load of 4.34×10^5 N. A safety factor of 3 is, therefore, provided. All 24 columns were proof-tested to a minimum of 6.65×10^5 N in compression at room temperature before installation.

Shell Construction & Cryogenic System

The helium shell is made from stainless steel 304 plates, assembled and welded to form a 12-sided polygonal annulus enclosing the coil. The lower shell is rectangular in cross section while that of the upper is larger and of strange shape (Fig. 4) to provide a 2000 ℓ liquid helium storage space. The total amount of liquid helium in the magnet is about 3000 liters.

The LN_2 temperature radiation shield is made of 0.8 mm copper sheets fabricated to the correct shapes and assembled with clips and self-taping machine screws. The thermal bridge (Figs. 3 and 4) of the columns provide mounting studs for the radiation shield to slide in and out on as the magnet is cooled down or warmed up.

The LN_2 system for CCM is a gravity-feed system (Fig. 5). It consists of an external 500 gal. (1850 liters) storage dewar, which supplies liquid to both the radiation shield and the intercepts on the columns, through cooling tubes that are attached to the Cu shield with specially designed flexible copper clips and rigidly attached to the thermal bridge of the columns via a mechanical arrangement. Indium is used in the latter to reduce thermal contact resistance. In all cases, the tubes slope upwards towards the top of the magnet.

The helium system, shown in Fig. 6, is also gravity fed. The vacuum shell is fabricated out of 3.175 mm (1/8") stainless steel (304) skin strengthened with ribs and cross bars.

Thermal Insulation

Radiation heat transfer in general contributes

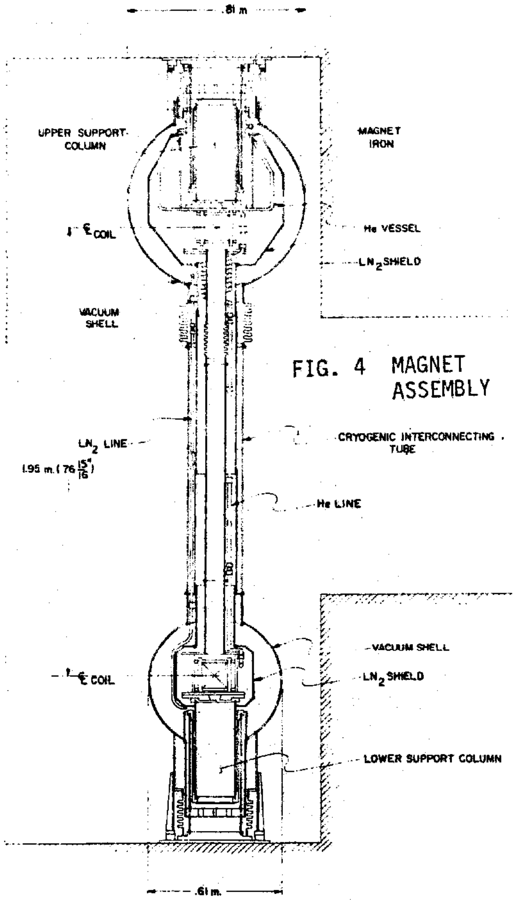


FIG. 4 MAGNET ASSEMBLY

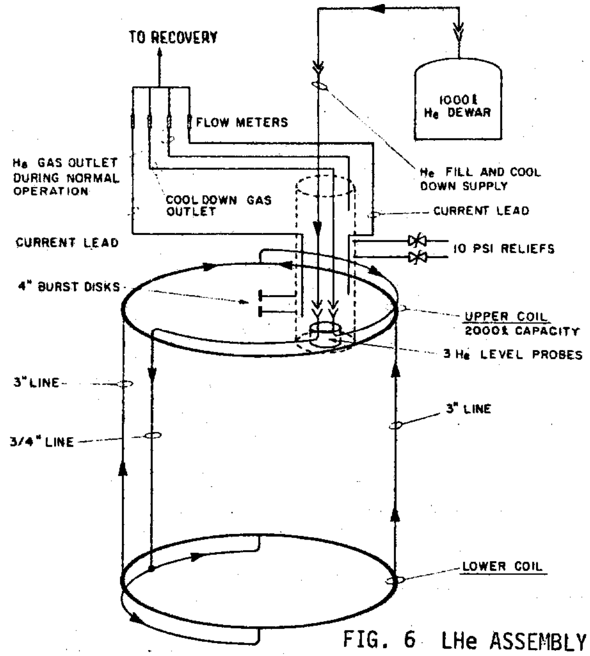


FIG. 6 LHe ASSEMBLY

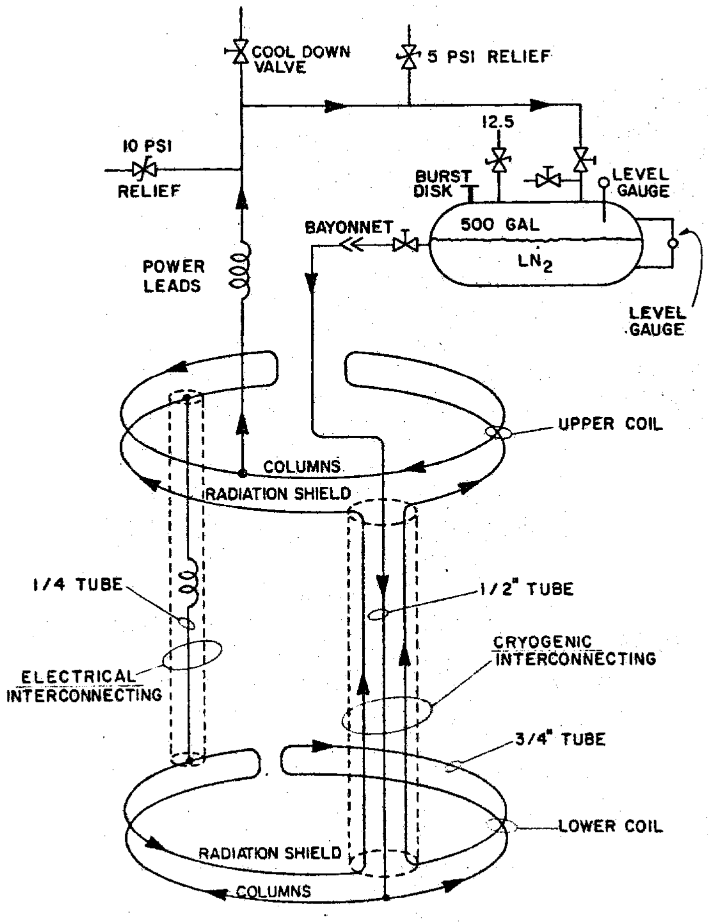


Fig. 5 LN_2 SYSTEM

significantly to the total helium boil-off of a large magnet. CCM has 70 m^2 of surface area for heat exchange. Special efforts were taken to provide high quality thermal insulation. Following a technique developed by the author,[4] twelve layers of 500 Å NRC-2 multilayer insulation were wrapped around the helium shells whose surfaces were previously covered with a reflective aluminum tape (3M #425). This method was measured to give a heat transfer rate of 15 mW/m^2, which is better than the 40 mW/m^2 usually used for magnet design. Between the radiation shield (78K) and the vacuum shell (300K), 40 layers of 300 Å NRC-2 were used.

Power Chimney and Instrumentation

The two coils are connected electrically and cryogenically together through two 7.62 cm interconnecting tubes, and the single chimney reduces conduction heat transfer from the outside world. Maximum operating current is 1000 A for CCM and the coils are powered through a pair of AMI leads[5,6] rated for 1625 A operation.

A fairly comprehensive protective system has been developed. CCM would automatically discharge and dump its energy into an external dump resistor (0.2 Ω) whenever one of the following conditions is detected:

1) Magnet ground current (possible short to ground)
2) Over current on magnet
3) Excessive voltage on current leads
4) Low LHe boil-off rate
5) High LHe boil-off rate
6) LHe level I (low LHe level or failure of probe)
7) LHe level II (low LHe level or failure of probe)
8) Overheating of the diode in the power supply
9) Improper access into the experimental radiation area

Cryogenic Test Results

Following a construction period of 2 years, the magnet (Fig. 7) was ready for pump down, a cool down and a low current test before installation into the CCM iron. The high humidity at the construction site (Meson Area Detector Building) during superinsulation and cold shock leak checking of the shells made the pump down a long and tedious process. In the end, we removed the

15.24 cm (6") burst disk on the upper vacuum shell and pumped with a 10.16 cm (4") cold trap and diffusion pump. Approximately 12 liters of water were removed from the system. Several small leaks in the vacuum shell were detected and readily fixed. (The vacuum shell contained over 1000 linear feet of weldment.)

We started cooldown when the vacuum read $\sim$ 100 millitorrs. Figure 8 shows the rate at which the two coils were cooled down. A liquid nitrogen precooling technique was used, which permitted both coils to be immersed in LN_2 before further cooling down with LHe. The total cryogen requirement was $\sim$ 4000 ℓ of LN_2 and $\sim$ 3000 ℓ of LHe. If we had cooled the coils down to only 90K instead of 78K, an additional 5500 ℓ of LHe would have been required for the cooldown.

The LHe boil-off rate was monitored for $\sim$ 5 days. It is estimated (Fig. 9) that the boil-off rate will eventually settle down at $\sim$ 13 ℓ/hr. Since the intercepts on the columns were running at 105K instead of the anticipated 80K, the LHe usage rate should be $\sim$10-11 ℓ/hr, after a higher pressure head is applied to the LN_2 cooling system. This is in reasonable agreement with the $\sim$ 8 ℓ/hr as predicted by calculation. Also, since this value is substantially less than the break even value of 40 ℓ/hr, the cryogenic performance is considered successful.

We then passed 10A through the coils. No ground shorts were detected. Various interlocks were also checked out. Unfortunately, we cannot fully charge the magnet to 1000 A until we have the coils installed in the CCM magnet iron. We had to warm up sooner than we would have liked to (before we can take all LHe boil-off data) because of a scheduling problem.

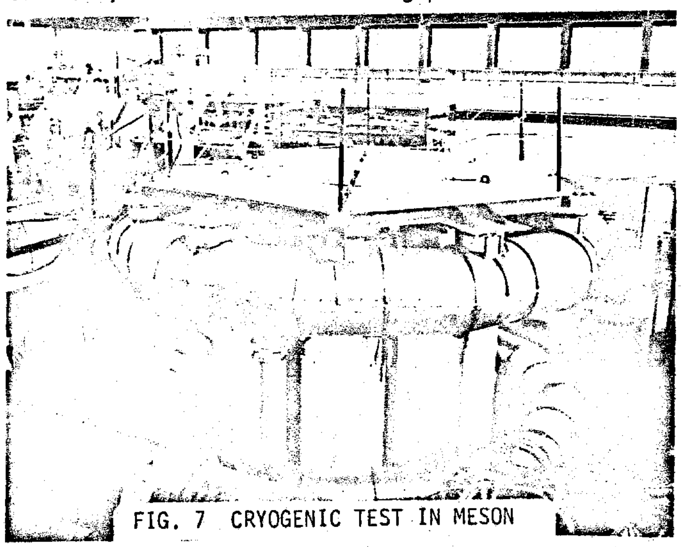
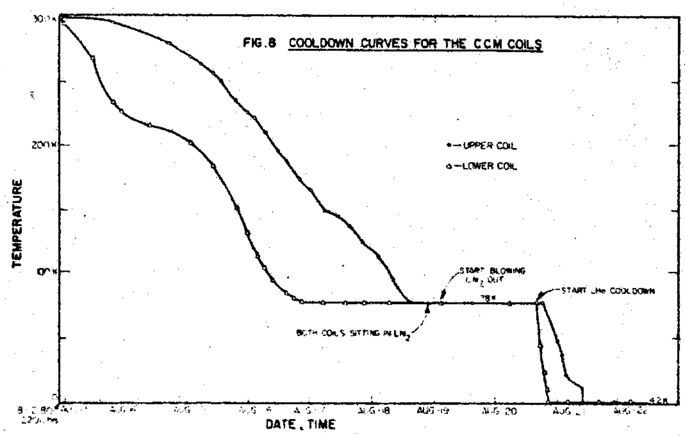
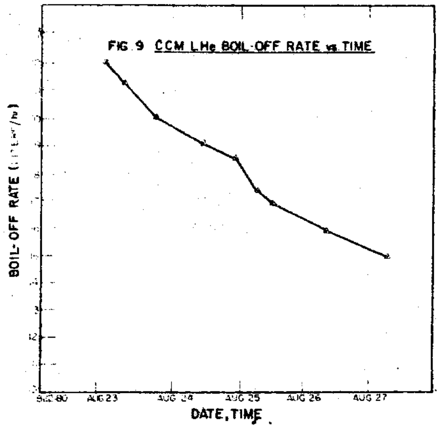


FIG. 7 CRYOGENIC TEST IN MESON





Future Plan

The Meson Test indicated that the superconducting coils are economically viable for the replacement of the old copper coils. The old coils are being removed from the Muon Lab. The CCM superconducting coils are expected to be fully charged in Dec. 1980 or Jan. 1981.

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References

1. Robert Lari, "Graphic, Time-sharing Magnet Design Computer Programs at ANL," Proc. 5th Int. Conf. on Magnet Technology, Rome (1975) p. 244-251.
2. C.W. Trowbridge, Proc. 4th Int. Conf. on Magnet Technology, Brookhaven (1972), p. 555.
3. E.M.W. Leung, "Magnetic Field Calculation of the Superconducting Version of the Chicago Cyclotron Magnet using GFUN-3D", FNAL TM-759 2751.000 (1978).
4. E.M.W. Leung, R.W. Fast, H.L. Hart and J.R. Heim, "Techniques for Reducing Radiation Heat Transfer Between 77 & 4.2K", Advances in Cryogenic Engineering, Vol. 25, p. 429 (1980).
5. Manufactured by the American Magnetics Inc.
6. K.R. Efferson, The Review of Scientific Instruments, Vol. 38, No. 12, p. 1776-1779, Dec. 1967.